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Early action on Paris Agreement allows for more time to change energy systems

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Abstract The IMAGE integrated assessment model was used to develop a set of scenarios to evaluate the Nationally Determined Contributions (NDCs) submitted by Parties under the Paris Agreement. The scenarios project emissions and energy system changes under (i) current policies, (ii) implementation of the NDCs, and (iii) various trajectories to a radiative forcing level of 2.8 W/m^2 in 2100, which gives a probability of about two thirds to limit warming to below 2 °C. The scenarios show that a cost-optimal pathway from 2020 onwards towards 2.8 W/m^2 leads to a global greenhouse gas emission level of 38 gigatonne CO_2 equivalent ($GtCO_2eq$) by 2030, equal to a reduction of 20% compared to the 2010 level. The NDCs are projected to lead to 2030 emission levels of 50 $GtCO_2eq$, which is still an increase compared to the 2010 level. A scenario that achieves the 2.8 W/m^2 forcing level in 2100 from the 2030 NDC level requires more rapid transitions after 2030 to meet the forcing target. It shows an annual reduction rate in greenhouse gas emissions of 4.7% between 2030 and 2050, rapidly phasing out unabated coal-fired power plant capacity, more rapid scale-up of low-carbon energy, and higher mitigation costs. A bridge scenario shows that enhancing the ambition level of NDCs before 2030 allows for a smoother energy system transition, with average annual

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emission reduction rates of 4.5% between 2030 and 2050, and more time to phase out coal capacity.

1 Introduction

All Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in Paris in December 2015 agreed to reduce global greenhouse gas (GHG) emissions to keep the increase in global mean temperature to well below 2 °C relative to pre-industrial levels, and furthermore to pursue efforts to limit this increase further to 1.5 °C (UNFCCC 2015a). Outlining the contribution to these GHG emission reductions, 161 Parties (representing over 97% of global GHG emissions in 2012) had submitted post-2020 Intended Nationally Determined Contributions (INDCs) to the UNFCCC by February 2016 (UNFCCC 2015b). The Paris Agreement entered into force on 4 November 2016, after it had been ratified by the required number of countries.[1] This re-asserts the process that started earlier. By 2009 in Copenhagen, countries had agreed to implement non-binding emission reduction proposals (pledges) for 2020 (UNFCCC 2009). Many countries representing about 75% of global 2010 emissions (UNEP 2014) had submitted reduction plans or pledges, which were later anchored in the Cancún Agreements (UNFCCC 2010).

The effect of the 2020 pledges on global emissions in that year has been analysed in various studies (e.g. Fekete et al. 2013; Hof et al. 2013; Kriegler et al. 2013a) and summarised in the UNEP Gap reports (UNEP 2013, 2014). In addition, several studies analysed whether countries are on track to meet their pledges and concluded that current policies are projected to result in global 2020 emission levels at the upper limit of the emission range resulting from the pledges (Climate Action Tracker 2015; den Elzen et al. 2015; Roelfsema et al. 2014; UNEP 2015). In a next step, both the pledges and current policies were found to lead to higher 2020 global emissions than cost-optimal 2 °C pathways (e.g. Jakob et al. 2012; Kriegler et al. 2013a, 2013b; Kriegler et al. 2014a, 2014b; Luderer et al. 2013a, 2013b; Riahi et al. 2013; Rogelj et al. 2013a, 2013b; van Vliet et al. 2012). However, these studies also concluded that achieving the 2 °C target with a likely chance (>66% probability) would still be technically feasible under delayed mitigation scenarios consistent with the pledges, i.e. only modest emission reductions up to 2020 and deep reductions thereafter.

Similar questions now apply to the NDCs for 2030. Recently, UNEP (2015) assessed the 2030 global emission levels consistent with meeting 2 °C with a likely chance based on existing delayed scenarios starting with cost-effective reduction after 2020. Several studies (e.g. den Elzen et al. 2016; Fawcett et al. 2015; Rogelj et al. 2016; Vandyck et al. 2016) concluded that the global emission level in 2030 resulting from the NDCs is considerably higher than the emission level of a cost-effective pathway to keep the global temperature increase below 2 °C (Clarke et al. 2014; UNEP 2015). This gap was acknowledged in the Paris Agreement and Parties agreed to submit new or updated national climate plans by 2020 (known as nationally determined contributions, so-called NDCs). The Agreement also established a process in which Parties put forward more ambitious NDCs every 5 years.

[1] By 10 April 2017, 143 of 197 Parties to the Convention had ratified, representing about 83% of global greenhouse emissions. With each country's ratification, its INDC becomes an NDC, which we use throughout this paper.

The effect of the NDCs and enhanced mitigation ambition needs to be assessed in light of this agreement. Such analyses could build on earlier studies that analysed the long-term impacts of short-term policies (e.g. Riahi et al. 2013) and could include the most recent assessments of the outcomes of the NDCs (e.g. Fawcett et al. 2015, Vandyck et al. 2016).

Our study assessed the long-term impacts of the NDCs and whether the internationally agreed 2 °C target can still be achieved in mitigation scenarios taking into account the NDCs. We also assessed the implications of enhancing the mitigation ambition of the NDCs, focusing on long-term effects on energy and land-use systems and the level of mitigation costs in achieving 2 °C emission pathways. This study goes beyond existing literature by building upon a detailed assessment of existing national policies, 2020 pledges and NDCs (i.e. as assessed by den Elzen et al. 2016). This consideration of current policies and the most recent international pledges and NDCs enables new insights into 2020 and 2030 emissions and energy projections and into how differences in timing and level of ambition of climate policy affect transition pathways.

2 Methods

2.1 Model framework

The scenarios in this study were analysed using the IMAGE integrated assessment modelling framework (Stehfest et al. 2014; van den Berg et al. 2015). The IMAGE framework is a simulation model with a recursive-dynamic (myopic) solution method, a partial equilibrium solution concept (price elastic demand), 26 world regions, and five economic sectors. This framework consists of a set of soft-linked models,[2] including a detailed energy-system model (TIMER), a land-use model (IMAGE land), and a global climate policy model (FAIR).

TIMER describes the long-term energy demand and production for different end-use and supply sectors. One hundred eighty energy end-use technologies and 54 energy conversion technologies are used, and substitution among technologies is described using the multinomial logit formulation. For most innovative technologies, technological progress is endogenously formulated on the basis of learning by doing. Inertia in capital stocks is included in the electricity generation sector, using a vintage formulation for the autonomous increase in energy efficiency. Retrofitting in the electricity sector is not simulated. The IMAGE land model looks into the long-term dynamics of the agricultural system and consequences for global land-cover. The agricultural system is described for seven agricultural crops and five animal product types.

Information of both baseline and mitigation options in the energy and land-use systems is forwarded to the climate policy model FAIR. The model is able to optimise global greenhouse gas emission pathways over time and across sectors and gases to achieve emission levels or climate targets at lowest cost, based on cumulative discounted abatement costs (using a 5% discount rate). For this purpose, the optimisation procedure employs a nonlinear, constrained, optimisation algorithm (the MATLAB FMINCON procedure; for further details, see van den Berg et al. 2015). The abatement costs in FAIR depend on baseline emissions and time-, baseline-, and regional-specific marginal abatement cost (MAC) curves from the other IMAGE framework models. Subsequently, the information on mitigation action (mostly carbon prices)

[2] Models run independently and exchange data.

is fed back from FAIR to the TIMER and IMAGE land models (in response, TIMER will for instance invest more in renewable energy).

For energy- and industry-related CO_2 emissions, MAC curves are determined by imposing a carbon price in the TIMER energy model and recording the induced reduction in CO_2 emissions. In order to capture the time- and pathway-dependent dynamics (due to technology learning and inertia related to capital-turnover rates) of the underlying TIMER model, MAC curves are derived for different reduction pathways and scaled in the FAIR model based on the actual implementation (van Vliet et al. 2012). For non-CO_2 emissions, the agriculture-related emissions from IMAGE land are combined with MAC curves based on Lucas et al. (2007) using updates of U.S. EPA (2013), Harnisch et al. (2009), and Schwarz et al. (2011). Given the detailed analysis of current policies and NDCs for land-use change and forestry (LULUCF), CO_2 emissions by the GLOBIOM/G4M team were used here instead of using IMAGE land, in combination with the response curves from the GLOBIOM/G4M models (Havlík et al. 2014; Böttcher et al. 2011; Kindermann et al. 2008) (see also Online Resources—Supplementary text). For calculating CO_2-equivalent emissions, 100-year Global Warming Potentials from IPCC AR4 are used (GHGs covered are CO_2, CH_4, N_2O, PFCs, HFCs, SF_6). The total abatement costs for each future year are calculated by FAIR as the total area under the MAC curves (TIMER-derived MACs, non-CO_2 MACs, and G4M land-use change MACs) at the determined regionally and time-specific carbon price levels.

2.2 Scenarios

The starting point for the calculations was the SSP2 (Shared Socioeconomic Pathways) scenario and its storyline as implemented in IMAGE (as described in detail in van Vuuren et al. 2016). The GDP and population projections were based on median assumptions, with population stabilising at 9 billion by 2050. Based on this scenario, a set of policy relevant scenarios was developed (see Table 1).

The current policies scenario was derived from the original SSP2 baseline by introducing explicit policy measures (Section 2.2.1). Subsequently, the two NDC scenarios were implemented by introducing a carbon price in order to meet the NDC goals of different countries (Section 2.2.2). In response to the price, measures are introduced in a cost-effective way throughout the model (i.e. in the energy and land-use system). Finally, three long-term climate policy scenarios were implemented meeting a long-term radiative forcing target consistent with staying below 2 °C, using a global carbon price (Section 2.2.3). These long-term policy scenarios start from different years (i.e. 2020, 2025, and 2030, as described below). Our study focused on the results for the 2010–2050 period, but the scenarios were developed for the full century.

2.2.1 Current policies scenario

The current policies scenario includes current climate and energy policies of major emitting countries, such as the assumed implementation of renewable energy share or capacity targets, power plant standards, fuel efficiency standards for cars, and carbon prices (den Elzen et al. 2015; Roelfsema et al. 2014). Carbon prices mainly impact the energy and industry sectors, by changing the price for energy carriers and as such influencing the choice for technologies in the multinomial logit equation, making low-carbon technologies relatively cheaper and high-carbon technologies more expensive. The measures are described in detail in Table S.1 (Online Resource). After the policy target year, the policy driver was discontinued. Policies may have a

Table 1 Overview of scenarios developed for this study

Scenario	Characteristics	Start year of cost-optimal mitigation	Emission level ($GtCO_2eq$)	
			2020	2030
Current policies scenario	Current policies of major emitting countries, assuming no new climate policies after policy target year			
Current policies	Implemented policies based on Den Elzen et al. (2015) (Online Resource Table S.1)	–	53.0	58.3
NDC scenarios	Following the 2020 pledges and 2030 emissions resulting from NDCs, constant carbon tax at 2030 value after 2030			
NDC high	Higher end of the 2030 emission projection range resulting from NDCs	–	48.7	50.1
NDC low	Lower end of the 2030 emission projection range resulting from NDCs	–	48.7	49.5
2.8 W/m^2 scenarios	Scenarios consistent with the 2 °C target, varying in level of ambition and timing of cost-optimal mitigation			
2.8 W/m^2-2020 action	Starting from 2020 pledges	2020	48.7	38.1
2.8 W/m^2-NDC	Starting from 2020 pledges and 2030 emission levels from *NDC high*	2030	48.7	47.6
2.8 W/m^2-NDC bridge	Starting from 2020 pledges and moving to 2030 emission levels from *NDC low*	2025	48.7	40.0

long-term effect through the induced technology learning effects (e.g. by additionally installed renewable energy technologies compared to the SSP2 baseline). LULUCF policies were implemented in the GLOBIOM/G4M model framework. The 2020 pledges were not included in this scenario, resulting in greenhouse gas emission projections deviating from the NDC and mitigation scenarios from 2010 onwards.

2.2.2 NDC scenarios

The *NDC high* and *low* scenarios start from emission levels in 2020 resulting from current policies and 2020 pledges, and 2030 emission levels resulting from the full implementation of the NDCs (based on den Elzen et al. 2016, see Online Resource Table S.1). However, we assumed that Kazakhstan, the Russian Federation, Turkey and Ukraine followed the current policies scenario, as it resulted in lower emissions than their respective NDCs (see also den Elzen et al. 2016). If current policies (Section 2.2.1) were found to be insufficient to reach the NDC targets, a carbon price was introduced to reach the emission levels resulting from the implementation of the 2020 pledge and the NDCs. The regional carbon prices that emerged under the NDCs in 2030 were kept constant thereafter, implying that emissions remain below the original current policies scenario. For model regions in which not all countries have a pledge or an NDC, the absolute emission reductions in 2020 and 2030 resulting from the country pledges and NDCs within the region were subtracted from the BAU. The emission projection resulting from South Korea's NDC was combined with BAU emission projections for North Korea because the IMAGE model has one Korea region. Similarly, the emission projections resulting from Australia's and New Zealand's NDCs were added to the Oceania region of IMAGE. Finally, Brazil's indicative 2030 target was used, while the USA's NDC for 2025 was extended to 2030 by linearly interpolating between the 2025 NDC and the USA's long-term emission reduction target for 2050.

NDC high The *NDC high* scenario represents the upper end of the range of emission levels expected to result from NDC targets. In addition to unconditional NDCs, some countries also have stronger targets, conditional on financial support. In the *NDC high* scenario, we considered only unconditional NDCs and the least ambitious of NDC emission target ranges, where applicable. Next to Kazakhstan, the Russian Federation, Turkey and Ukraine, India followed the current policies scenario, as it resulted in lower emissions than its NDC. The NDCs for all other countries were assumed to be achieved domestically by not allowing international trade of emission credits until 2030.

NDC low The *NDC low* scenario represents the lower end of the range of NDC emission levels. In addition to unconditional NDCs, we also considered conditional NDCs in *NDC low.* Where countries provided emission target ranges, the most ambitious value was taken. For India, *NDC low* followed the current policies scenario (which satisfied the intensity target as stated in the NDC) like the *NDC high* scenario, but in addition included the effect of the renewable energy target.

2.2.3 Mitigation scenarios consistent with the 2 °C climate target

The three long-term mitigation scenarios start from the emission levels in 2020, 2025, and 2030 based on the NDC scenarios. The long-term climate target of the various scenarios in this group was set to 2.8 W/m^2 in 2100. This value is within the “likely below 2 °C” range from IPCC: 2.3–2.9 W/m^2 (Clarke et al. 2014). The 2.8 W/m^2 scenarios have a chance of about two third of staying below 2 °C at the end of the century, allowing for a lower chance or a temperature overshoot before. We assumed this to be consistent with the Paris Agreement’s goal to limit global warming to well below 2 °C. Achieving more ambitious targets, e.g. staying below 2 °C with a higher likelihood, is difficult in the model given the delay assumed in the *NDC high* scenario. The mitigation scenarios assumed full availability of mitigation technologies, meaning the model was allowed to use negative emission technology, specifically biomass with CCS, reforestation, and afforestation.

2.8 W/m^2-2020 action Up until 2020, the pledge assumptions determined the emission pathways. After 2020, a cost-optimal emission reduction pathway towards the long-term climate target by means of a global carbon price was implemented. In the *2.8 W/m^2-2020 action* scenario, Brazil, India, Japan, Russia, and Ukraine followed the current policies scenario, because it resulted in lower emissions than the 2020 pledges.

2.8 W/m^2-NDC To analyse the transition from the unconditional NDCs in 2030 to the 2.8 W/m^2 climate target, the *2.8 W/m^2-NDC* scenario started from the 2030 emission levels of the *NDC high* scenario. International trade was not allowed until 2030, reflecting the domestic nature of the unconditional NDCs. After 2030, a cost-optimal emission reduction pathway by means of a global carbon price was implemented. Some unconditional NDCs are overachieved in this scenario due to mitigation effort starting in 2030 (a result of TIMER using projected future carbon prices to steer investment decisions; de Boer and van Vuuren 2017).

2.8 W/m^2-NDC bridge To study the implications of strengthening the ambition level of NDCs, the *2.8 W/m^2-NDC bridge* scenario followed the emission pathway of the *NDC low* scenario up to 2025, effectively starting in 2020 from the 2020 pledges moving towards the 2030 emission levels of the *NDC low* scenario. However, after 2025, a cost-optimal emission reduction pathway by means of a global carbon price was implemented.

3 Results

3.1 Global greenhouse gas emissions

We focus the discussion of results on the current policies scenario and the 2.8 W/m^2 scenarios. Under the current policies scenario, global emission levels are projected to increase between 2020 and 2050 (Fig. 1, and Online Resource Fig. S.1 for projections through 2100). In contrast, implementation of NDCs is projected to result in a peak in global GHG emissions in 2030. By 2030, GHG emissions reduce by 14% (*NDC high*) to 15% (*NDC low*) compared to the current policies scenario. Between 2030 and 2050, emissions stabilise due to an autonomously decreasing GHG intensity of the economy. Enhancing NDC ambition as in the *2.8 W/m^2-NDC bridge* scenario resulted in a GHG emission reduction of 31% by 2030 relative to the current policies scenario. GHG emissions are projected to be approximately 38 GtCO_2eq in 2030 under the *2.8 W/m^2-2020 action* scenario, a reduction of 20% on 2010 levels. In contrast, the NDCs are projected to lead

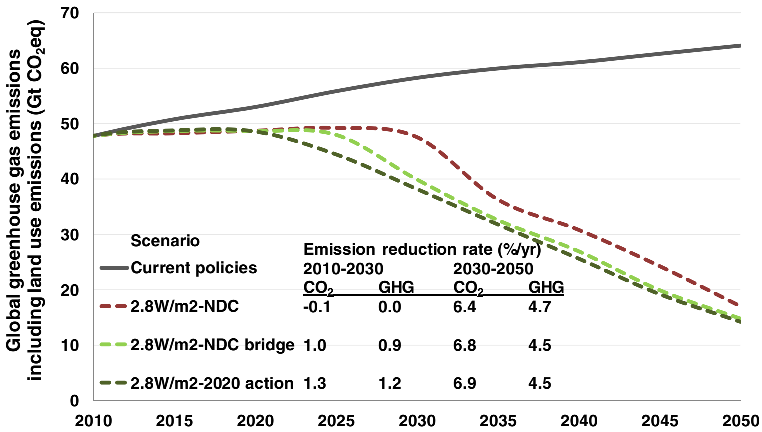

Fig. 1 Global GHG emissions ($GtCO_2eq$/year) between 2010 and 2050, including CO_2 emissions from land use, under the current policies scenario (*solid line*), and the 2.8 W/m^2 scenarios (*2.8 W/m^2-NDC*, *2.8 W/m^2-NDC bridge* and *2.8 W/m^2-2020 action*; *dashed lines*)

to 2030 emission levels of approximately 50 $GtCO_2eq$, an increase of 5% on 2010 levels (see Online Resource Fig. S1).

GHG emission reductions between 2010 and 2050 in the three 2.8 W/m^2 scenarios range from 64 to 70% (including LULUCF). In the *2.8 W/m^2-NDC* scenario, GHG emissions are projected to be reduced from 47.6 $GtCO_2eq$ in 2030 to 17.1 $GtCO_2eq$ in 2050. This required average rates of GHG emission reduction of 4.7%/year between 2030 and 2050. The *2.8 W/m^2-NDC bridge* scenario showed a similar GHG emission level by 2050 (14.8 $GtCO_2eq$), but the reduction rate was lower (4.5%/year) as emissions in 2030 are projected to be 40.0 $GtCO_2eq$. The *2.8 W/m^2-NDC* scenario also showed larger emission reductions after 2050 to compensate for the extra emissions before 2050 (Fig. S.1).

Figure 2 shows global sectoral emissions until 2050. Under the current policies scenario, emissions in most sectors are projected to remain constant or increase between 2010 and 2050, except for LULUCF emissions. In contrast, emissions are projected to decrease strongly under the 2.8 W/m^2 scenarios. Total emissions are projected to be reduced by 18% in the *2.8 W/m^2-NDC* scenario and by over 30% in the *2.8 W/m^2-NDC bridge* and *2.8 W/m^2-2020 action* scenarios by 2030, compared to the current policies scenario (see also Online Resource Fig. S.2). By 2050, the smaller short-term emission reductions in the *2.8 W/m^2-NDC* scenario are starting to be compensated, with total emission reductions of 73% relative to the current policies scenario, compared to 77% under *2.8 W/m^2-NDC bridge* and *2.8 W/m^2-2020 action*.

Although all sectors contributed to reducing GHG emissions, the power sector showed the largest reductions between 2020/2030 and 2050, as this sector is assumed to have the largest potential to reduce emissions by changing the power mix (from fossil fuels to renewables, nuclear, and fossil fuels/biomass with CCS; see Fig. S.3). The power sector is projected to be fully decarbonised before 2050 under all 2.8 W/m^2 scenarios, but decarbonisation took place at a higher rate under *2.8 W/m^2-NDC* than under *2.8 W/m^2-NDC bridge* to compensate for the delay in optimal mitigation. Early retirement of existing coal-fired power plants was required in all 2.8 W/m^2 scenarios, but especially in the *2.8 W/m^2-NDC* scenario (as discussed further in Section 3.2). Reductions in the industry sector were related to reduced energy intensity, most notably in steel production. Most emission reductions in the building sector were achieved through efficiency improvements in space heating, space cooling, and household appliances.

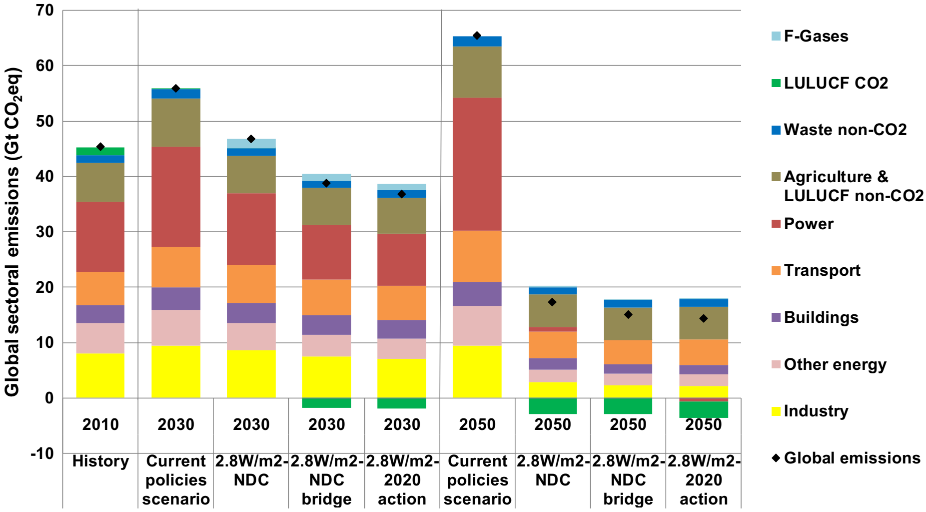

Fig. 2 Global GHG emissions ($GtCO_2eq$) in 2010, 2030 and 2050 per sector and scenario. LULUCF: land use, land-use change and forestry. The category 'Other energy' consists of energy CO_2 emissions in other sectors than transport, power, industry and buildings, as well as energy non-CO_2 emissions

These efficiency improvements resulted in lower electricity use and final energy intensity of GDP. In the transport sector, electrification played a large role in reducing emissions.

Land-use CO_2 emissions were projected to decrease strongly as well, turning negative between 2020 and 2030. Reductions in land-use CO_2 emissions resulted from enhanced CO_2 uptake by forests due to afforestation and reforestation, and decreased CO_2 emissions due to reduced deforestation. Non-CO_2 emission reductions between 2020 and 2050 in the 2.8 W/m^2 scenarios mainly came from reductions in energy-related CH_4 and F-gas emissions. F-gases and energy-related N_2O and CH_4 emissions ('Other energy' in Fig. 2) showed the strongest relative reductions, both between 2020 and 2050 and against the current policies scenario in 2050. Reducing agricultural non-CO_2 emissions is assumed to be challenging, as the 2.8 W/m^2 scenarios showed only minor reductions in this category (Fig. 2).

3.2 Effects on the global energy system

Under the *2.8 W/m^2-NDC* scenario, primary energy use is projected to be 9% lower than under the current policies scenario by 2030, while under the *2.8 W/m^2-NDC bridge* and *2.8 W/m^2-2020 action* scenarios, the reduction is about 17 to 20%. The *2.8 W/m^2-NDC* scenario showed the largest reductions in primary energy use between 2030 and 2050: 16%, versus only 5% in *2.8 W/m^2-2020 action* and 7% in *2.8 W/m^2-NDC bridge* (Fig. 3). The reductions in the *2.8 W/m^2-NDC* scenario were mostly realised by rapidly scaling down the use of coal without CCS, which helped compensate for the smaller reduction in energy use until 2030. Penetration of non-biomass renewables is similar in all 2.8 W/m^2 scenarios by 2050, as the *2.8 W/m^2-NDC* scenario already includes quite a lot of non-biomass renewables in 2030. In the current policies scenario, in contrast, primary energy use is projected to increase further towards 2050, including the use of fossil fuels without CCS.

Under the *2.8 W/m^2-NDC* scenario, electricity demand is projected to be 7% lower than under the current policies scenario by 2030, while under the *2.8 W/m^2-NDC bridge* and

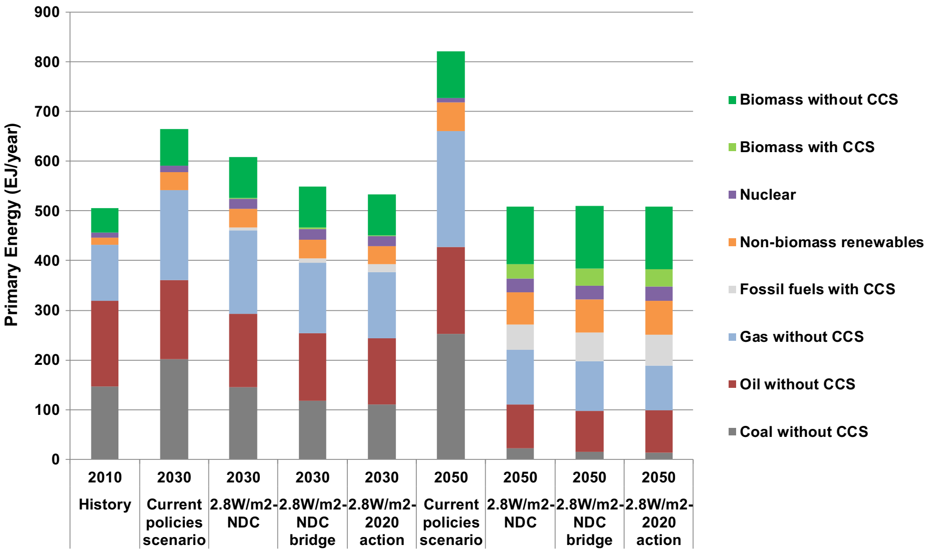

Fig. 3 Global primary energy use (EJ/year) in 2010, 2030 and 2050 in the current policies scenario and the 2.8 W/m^2 scenarios (*2.8 W/m^2-NDC*, *2.8 W/m^2-NDC bridge*, and *2.8 W/m^2-2020 action*). Non-biomass renewables are solar energy, wind energy, hydropower, and geothermal energy. *CCS* carbon capture and storage

2.8 W/m^2-2020 action scenarios, the reduction is about 15 to 18%. By 2050, electricity demand in all *2.8 W/m^2* scenarios is projected to be approximately 30% lower than under the current policies scenario, which indicates that by 2050, the delayed 2.8 W/m^2 scenarios have caught up with the *2.8 W/m^2-2020 action* scenario. Energy savings, measured as the difference in secondary energy use between the 2.8 W/m^2 scenarios and the current policies scenario, are 16% for *2.8 W/m^2-2020 action*, 13% for *2.8 W/m^2-NDC bridge*, and 6% for *2.8 W/m^2-NDC* in 2030, and around 35% (*2.8 W/m^2-2020 action* and *2.8 W/m^2-NDC bridge*) and 34% (*2.8 W/m^2-NDC*) in 2050.

The 2.8 W/m^2 scenarios resulted in lower total installed electricity capacity compared to the current policies scenario, approximately 4 to 10% in 2030 and 16 to 21% in 2050. Coal capacity is projected to be phased out starting in 2036 and before 2070 due to the increasing price of carbon in the 2.8 W/m^2 scenarios (electricity production based on coal is phased out earlier, around 2050). From 2025 (*2.8 W/m^2-2020 action*) to 2029 (*2.8 W/m^2-NDC*) onwards, no investment in new plants occurs. In addition, early retirement of existing capacity contributes to the decline of coal capacity from 2036 (*2.8 W/m^2-2020 action*) to 2040 (*2.8 W/m^2-NDC*) onwards, driven by the carbon price. Under the *2.8 W/m^2-NDC bridge* scenario, almost all existing coal-fired power plant capacity is projected to be phased out between 2030 and 2060. The *2.8 W/m^2-NDC* scenario required a faster transition: phase-out of coal-fired power plants started about 5 years later than under *2.8 W/m^2-NDC bridge*, but took place over a shorter period (Fig. 4 and Online Resource Fig. S.4). After coal, electricity production based on gas is projected to be phased out, with some gas capacity remaining as backup. In contrast, the installed power capacity of renewable energy is projected to increase between now and 2050 (Fig. 4), with larger increases, also after 2050, for *2.8 W/m^2-NDC* than for *2.8 W/m^2-NDC bridge*. As a result of these early retirements and the increased use of renewable energy sources, the share of fossil fuels (coal, oil, and natural gas) without CCS in primary energy supply is projected to be reduced considerably in the 2.8 W/m^2 scenarios, from 85% in 2010 to 37–43% in 2050.

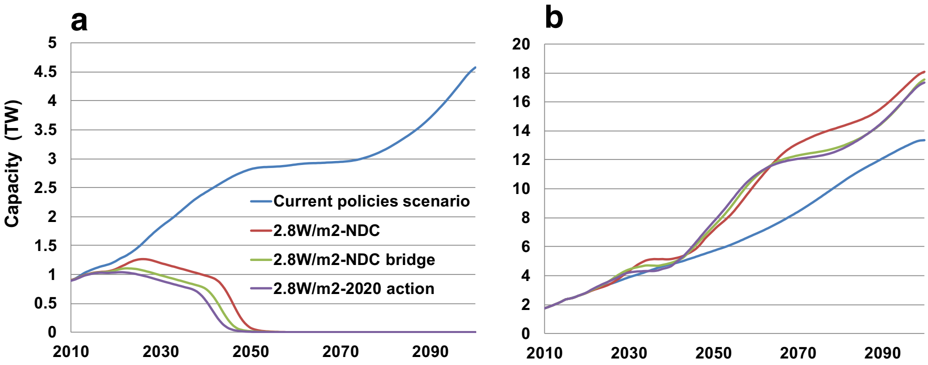

Fig. 4 Installed power capacity (TW) between 2010 and 2100 in the current policies scenario and the 2.8 W/m^2 scenarios (*2.8 W/m^2-NDC*, *2.8 W/m^2-NDC bridge*, and *2.8 W/m^2-2020 action*). Panel **a** coal without CCS, panel **b** renewables and nuclear

The mitigation scenarios relied on the availability of all possible technologies, especially on energy efficiency improvements and negative emissions from the land use, energy, and industry sectors. CCS was deployed to reach negative emissions in the energy and industry sectors, but it only started playing a significant role after 2050. The share of CCS (used with biomass and fossil fuels) is projected to increase from 0% of total electricity production in 2010 to approximately 13–18% in 2050 under the 2.8 W/m^2 scenarios, with BECCS taking up 7–8% of total electricity production (Online Resource Fig. S.3). Also the share of nuclear is projected to increase after 2020, reaching 5.5% (*2.8 W/m^2-2020 action*) to 5.6% (*2.8 W/m^2-NDC*) of total primary energy use and 21% (*2.8 W/m^2-2020 action)* to 23% (*2.8 W/m^2-NDC*) of electricity production by 2050.

In the near term, the share of renewables and low-carbon energy sources[3] in primary energy use in the 2.8 W/m^2 scenarios (23–26% in 2030) is projected to be only slightly higher than in the current policies scenario (18%) (Online Resource Table S.2). In the long-term, however, the energy system shows a complete transformation with the share of low-carbon energy sources in primary energy supply increasing from 15% currently to 61–63% by 2050 and further increasing afterwards in the *2.8 W/m^2-2020 action* and *2.8 W/m^2-NDC bridge* scenarios. The *2.8 W/m^2-NDC* scenario catches up in the second half of the century, reaching 57% by 2050 and the highest installed renewable power capacity of all scenarios after 2050 (Fig. 4), with extra wind, solar and nuclear capacity going into operation around 2050. The shares of low-carbon energy sources in power supply are even higher, due to a phase-out of fossil fuels without CCS and increased investments in renewable energy. Solar PV, wind, hydropower and nuclear are responsible for about three-quarters of global power supply by 2050 under the mitigation scenarios. The remainder is approximately equally divided between fossil fuels with CCS and BECCS.

3.3 Effects on global costs

The implementation of climate policies, pledges, and NDCs in the 2.8 W/m^2 scenarios is projected to significantly reduce GHG emissions and energy use, but this comes with additional costs. As a metric of costs, annual abatement costs expressed as percentage of GDP were used. The annual abatement costs are projected to be high early in the *2.8 W/m^2-2020 action* scenario,

[3] Biomass with and without CCS, nuclear, non-biomass renewables, and oil, coal, and gas with CCS

but these are compensated by lower costs than the other scenarios later on in the century (Online Resource Fig. S.5). While the *2.8 W/m^2-NDC* scenario is projected to lead to lower costs in the short term, its annual abatement costs are the highest of all scenarios from 2050 onwards. The *2.8 W/m^2-NDC bridge* scenario resulted in costs similar to the *2.8 W/m^2-2020 action* scenario, with slightly lower costs until 2035. Costs are very similar across scenarios by 2025, because even though the reductions in the *2.8 W/m^2-2020 action* scenario are higher, these reductions are assumed to be implemented cost-optimally over regions. In the other scenarios, every region has a different carbon price level to achieve their NDCs domestically, which leads to higher global costs per ton of GHG emissions reduced. Cumulative abatement costs are projected to be highest in the *2.8 W/m^2-NDC* scenario, being 18% higher than cumulative costs of the *2.8 W/m^2-2020 action* scenario in the 2010–2100 period (with a 5% discount rate; Fig. S.5). The scenario that delays action thus resulted in both higher annual abatement costs in the long run and higher cumulative abatement costs, compared to a scenario that takes early action.

4 Discussion and conclusions

This study assessed the long-term impacts of the NDCs and the effect of enhancing their mitigation ambition on changes in energy systems and the level of mitigation costs in achieving 2 °C emission pathways (2.8 W/m^2 radiative forcing target; about a two third chance of holding warming to below 2 °C). In the 2.8 W/m^2 pathways, GHG emission reductions between 2020 and 2050 mainly came from reductions in energy-related CO_2 emissions. These emission reductions in the energy system were achieved by a combination of enhancing efficiency and scaling down the use of fossil fuels (no investment in new plants and early retirement of existing capacity), while increasing deployment of low-carbon energy sources.

The results are relevant in light of the review mechanisms and instruments to enhance mitigation ambition included in the Paris Agreement. Our results confirm findings of earlier studies, based on more abstract representations of current policies and pledges, that achieving the 2 °C target is possible under scenarios that delay optimal mitigation if fast emission reduction are realised after 2020 (Kriegler et al. 2013a; Riahi et al. 2013; Tavoni et al. 2015). Projected 2050 emissions resulting from the 2.8 W/m^2 scenarios are in line with other estimates, such as Riahi et al. (2013), who reported 18–28 $GtCO_2e$ by 2050 for scenarios that assumed pledges emission levels in 2020 and delayed action until 2030. The range in emission projections resulting from the 2.8 W/m^2 scenarios is further in line with the 40–70% emission reduction on 2010 levels by 2050 globally, as reported by the IPCC for RCP 2.6 scenarios[4] (IPCC 2014).

Differences in sectoral emissions are larger between the *2.8 W/m^2-NDC* scenario and the *2.8 W/m^2-NDC bridge* scenario than between the *2.8 W/m^2-NDC bridge* and *2.8 W/m^2-2020 action* scenario. This suggests that the effects of a 5-year delay in action between 2020 and 2025 are smaller than the effects of 5-year delay between 2025 and 2030.

The emission reduction rates found for the 2.8 W/m^2 scenarios fall within the range reported in IPCC AR5 (CO_2 approximately −2 to −7.5% per year between 2030 and 2050 for scenarios with 2030 emissions between 50 and 55 $GtCO_2eq$; Clarke et al. 2014). Riahi et al. (2013) reported an average CO_2 emission reduction rate of 7% per year between 2030 and 2050 for a scenario that accounted for a continuation of the

[4] 2.8 W/m^2 belongs to this category (2.3–2.9 W/m^2).

unconditional 2020 pledges towards 2030. The *2.8 W/m^2-NDC* scenario showed comparable CO_2 emission reduction rates of 6.4% per year in that period. The 2.8 W/m^2 scenarios are ambitious compared to historical 20-year average annual emission reduction rates; only in short time periods, rates of 2 and 3% have been observed and primarily due to economic recessions (Riahi et al. 2013).

The projected emission reduction rates and energy transition may be difficult to accomplish in reality for various reasons. First of all, the modelled energy system transformations depended on the availability of all technologies, including socially debated ones such as biomass or CCS, which are needed to realise negative emissions. The reliance on negative emissions technology in the second half of this century is larger in the *2.8 W/m^2-NDC* scenario than in the other 2.8 W/m^2 scenarios. Social preferences and non-rational behaviour are not included in our model, but these are expected to impact the structure of the energy system and thus global emission projections. These preferences could lead to an acceleration of the energy system transition in specific sectors (e.g. electric transport or residential solar), but also to lock-in in conventional systems in other sectors, resulting in a delay and a lower probability of meeting the Paris Agreement's 2 °C goal. Especially social resistance against the use of biomass (in light of food security or biodiversity) and CCS, as well as investors' resistance to early retirements of power plants, could decrease the probability of meeting the 2 °C goal in practice. Second, the rapid emission reductions shown by the model may be difficult to realise due to political and institutional inertia. It should be noted that also different assumptions on the main drivers of technology change may play a role (see also Gerlagh et al. 2009 and van Vuuren et al. 2004 for a discussion of optimal timing of climate policy). To account for these factors, an analysis of the transitions at the country level would be an interesting topic for future research (e.g. van Sluisveld et al. 2013).

Given these considerations, the following conclusion can be drawn.

Enhancing the ambition level of NDCs before 2030 can allow for a smoother energy system transition, with lower annual emission reduction rates (4.5% instead of 4.7% between 2030 and 2050) and more time to phase out unabated fossil fuels. It can further result in lower total mitigation costs for meeting the 2.8 W/m^2 target. Implementing no further GHG emission reductions by 2030 than currently formulated NDC reductions would require very rapid reductions after 2030 to meet the 2 °C target with a chance of about two thirds. The cost-optimal pathway towards 2.8 W/m^2 leads to global greenhouse gas emissions of 38 $GtCO_2eq$ by 2030, a reduction of 20% on 2010 levels. In contrast, the NDCs are projected to lead to 2030 emission levels of 50 $GtCO_2eq$, an increase of 5% relative to 2010. The NDC 2.8 W/m^2 scenario delays mitigation and thus requires more rapid transitions after 2030 to meet the 2.8 W/m^2 target.

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